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Idai Damage Assessment From the Sentinel-1 Radar Satellite

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Abstract

For disaster emergency response, timely information is critical and satellite data is a potential source for such information.This paper shows, in the context of Cyclone Idai that hit Central Mozambique in March 2019, that Change Detection between pairs of Synthetic Aperture Radar (SAR) data, combined with external data on the location of houses prior to the cyclone, provide an assessment of building damage. The free availability of SAR data from Sentinel-1, with further automated processing of it, means that this analysis is a cost-effective and quick potential first indication of cyclone destruction. Importantly, the first SAR data was available 12 hours after first impact, while the final analysis based on optical images was not available until 21 days later.

1 Intriduction

The tropical Cyclone Idai formed off the east coast of Mozambique on March 4, 2019, and made landfall on March 14, close to the city of Beira. The city was heavily impacted by the cyclone with both strong winds and heavy rains, resulting in severe damage. As is often the case, optical satellites' view of the city was covered by clouds for days before and after the landfall, making it difficult to assess the damage severity. The last cloud-free image was on March 2, while the first cloud-free images of the city after the cyclone were available on March 26, almost two weeks after the impact. A full assessment of the city based on optical satellite images were not available until April 4, three weeks after the cyclone hit Beira. In contrast, SAR data from Sentinel-1 was available 12 hours after first impact and new assessments could have been done every 6 days after that, providing four assessments over time before the full analysis from optical images was available. However, SAR is visually harder to interpret and is not an easy alternative to high resolution optical images. This paper shows that SAR does pick up damage from the cyclone if processed by means of statistical change detection. Further, filtering by knowledge of location of houses, the analysis can be focused on damage to structures, which is often a key interest in emergency response as this is correlated with socio-economic impact [12].

2 Data

2.1 Sentinel-1

The input data for the Change Detection analysis is from the European Space Agency's Sentinel-1 SAR satellite, that provides data for free [6]. Generally, Sentinel-1 plans for 6 days interval between imagery of land within Europe and 12 day intervals outside Europe [6]. However, 6 day intervals are also occasionally available outside Europe as in this case of the cyclone Idai.

2.2 Spatial Characteristics of Beira

For spatial analysis of the cyclone's impact, a grid of square cells is used, which is referred to as Unit-of-Analysis (UA). The grid was adopted from [11], and consists of 115m x 115m cells covering residential areas of the city. This means that non-residential areas of the city, like industry and airport are filtered out. Each cell is associated with geographical and demographic parameters, such as distance to the coast in direction of the cyclone, poverty, and construction density. The latter two data variables are extracted from a previous study on local poverty [11]. This UA grid allows for alignment of the different variables/parameters to which statistical analysis of their dependence can be applied.

2.3 OpenStreetMap - Buildings

Building damage, in particular, is closely related to saving lives in emergency response [12]. To focus the analysis on this critical element, results are filtered by prior knowledge of the location of houses. The building polygons from OpenStreetMap (OSM) [10] are used for this. Other alternatives, like the Global Urban Footprint [7,8], were also explored, but visual inspection found that OSM had the best coverage and the highest accuracy.

2.4 World Weather Online

Weather data on the cyclone was downloaded from the World Weather Online database [1]. The weather data used is the precipitation, the wind and gust speed, all measured as daily daytime averages (between 6am - 6pm).

3 Method

This paper uses the Change Detection method developed by Nielsen, Conradsen and Skriver [3] for damage assessment after a cyclone. The method, along with the further development [4], has been applied to various other challenges such as flood and wetlands monitoring, deforestation, arrivals and departures of large sea vessels as well as aircraft, and arms control [2].

The methodology presented here for cyclone damage assessment is based on SAR Change Detection following the complex Wishart change detection statistic [3, 5]. The complex Wishart test statistic has the advantage of being able to test for differences in mean values on pixel wise covariance matrices from SAR sensors with polarimetric capabilities. For cyclone urban damage assessment, it can be applied over two SAR images, one prior to the peak impact, as well as any other two points in time. This Change Detection approach is advantageous to simpler techniques as the test statistic provides a probability for change at each pixel position, allowing for thresholding according to a certain rate of false-positive detections (significance level). Additionally, the method offers a statistical way of combining the information in all channels from a given polarimetric SAR sensor into a single variable. In the case of the Sentinel-1 (VV, VH), a dual polarimetric sensor, a simple ratio Change Detection would lead to two change metrics for each pixel. In this paper a threshold of 95 percent is used as indicating a significant change between two points in time. Additionally to a change probability, one might be interested in the direction of the change, as an indication of whether a decrease or increase in radar intensity was observed from an image at time 1 to the image at time 2. The Loewner measure captures the direction of change [9].

It is clear that with a resolution of 20 m $\times$ 22 m, and with Beira generally containing many small houses, we are not able to pinpoint individual houses that are damaged to the same extent as the *manual tags* based on high resolution images with sub-meter pixel resolution. The aim is to get a general overview of disaster impact that can guide emergency response. This could for example be done by producing count of changes over larger blocks, such as the UA grid cells presented in the previous section. In the following section, results from such an approach is presented along with a validation study.

4 Results

4.1 Weather and Change Detection

A necessity for the relevance of SAR data, is that the Change Detection picks up changes that can be clearly related to Idai. Idai hit Beira on March 14, with both high winds and heavy rains lasting for days until March 18. The peak of the cyclone was registered on March 15. The weather associated with the cyclone in Beira is shown as lines in Figure 1, while the impact assessed by *changes* are shown as columns. The *changes* clearly reflect the weather data, with many detections between March 14 and March 20. The number of detected changes between March 14 and March 20 are almost 10 times larger than the observed change in a "normal" period (March 2 to 14) prior to the arrival of Idai. The passing over Beira of both Sentinel-1 A and B satellites at two different times during March 14 provides further evidence that the SAR data is reflecting Idai. The very high wind speeds of the cyclone Idai started on the 14 of March 2019. On this day, the A-satellite passed Beira at 3.09AM, within relative orbit (RO) 6, and the B-satellite passed at 4.06PM, within RO-101. This time difference means that RO-6 did not capture many changes between March 2nd and March 14, but a large difference between March 14 and 20, as there had been limited change at 3 AM on March 14. RO-101 on the other hand, captured a large number of changes between February 18 and March 14, as weather had turned worse as this satellite passed at 4 PM, though the cyclone had still not reached its peak. This also means that the very first data on the impact from Idai was available in RO-101 within 12 hours of the onset of the cyclone. Receiving and processing the data for change maps can also be done in hours. This highlights the advantage of the SAR data, as opposed to the analysis based on optical images or UAVs, that were not available until much later.

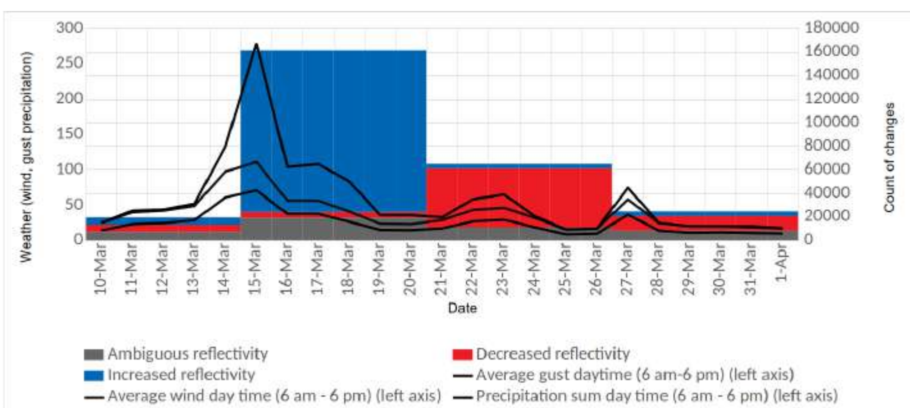
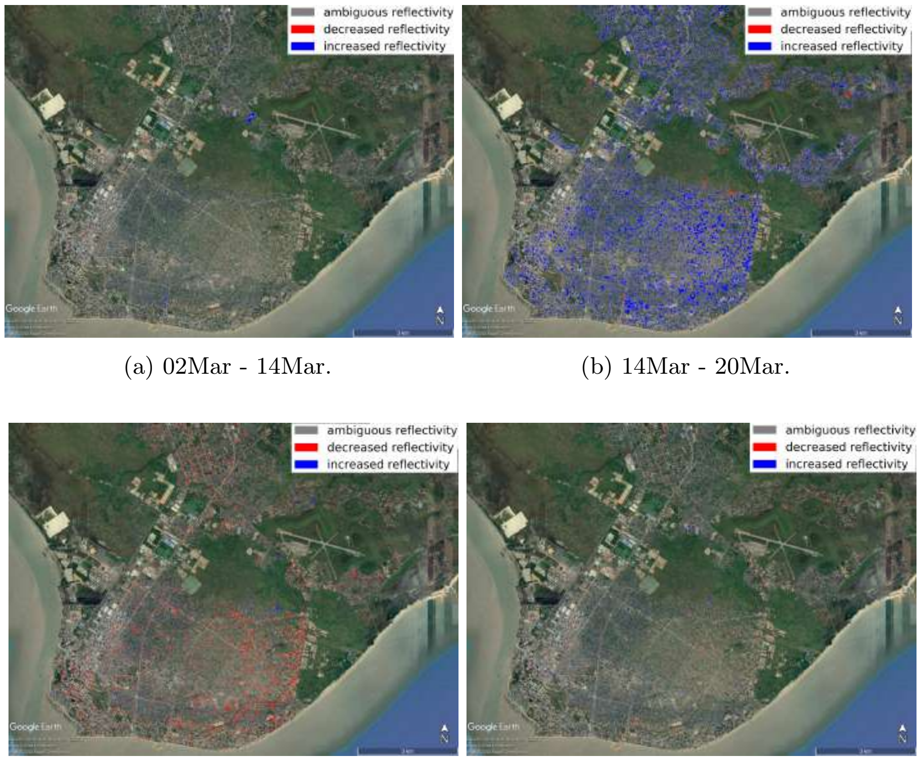


Figure 1: emphchanges in SAR data and weather data (wind-speed, gust and precipitation) around the peak of Idai's intensity. The counted *changes* are over the entire over urban area using the data from the (RO) 6 Sentinel Satellite A.

4.2 Different Types of Change

By nature it is difficult to interpret the type of event that leads to a change in a SAR Change Detection analysis. The change in itself is a result of a change in the reflection strength of the emitted radar wave. An increased strength of the reflection, for example, is not unambiguously decided by one type of event, but when narrowing a change analysis down to a time interval in which a cyclone has its peak impact, the majority of change can be associated with effects from this event. In the analysis of the cyclone Idai, large changes are both observed in the days covering the peak of the cyclone (March 14 to 20) as well in the period immediately after(March 20 to 26). In the period, with extreme weather (March 14 to 20), the radar show *increased reflections*, while in the period immediately following the peak (March 20 to 26) is characterized by *decreased reflections*. Several phenomena could lead to this pattern, though it is difficult to exactly interpret the polarimetric scattering mechanism in a complex urban environment with multiple reflectors. For example, houses that lose their roofs could change from a plane reflector to a trihedral from the inner corners of the house, causing an increased reflection. When the roof is repaired, either temporarily or more permanently, the reflection would decrease relatively again. Multiple reflections are also likely to happen in an urban environment causing high peak intensities, that changes when houses are demolished by the cyclone. The *decreased reflections*, could be due to a clean-up, with the removal of building debris and rebuilding of roofs/temporary roofs. Though filtered by location of houses, it cannot be ruled out that some change in reflection might also be due to change in saturation of water in the soil.

Figure 2 shows the output from the Change Detection analysis on a zoom of central Beira at different times before, over, and after the cyclone impact.



(a) 02Mar - 14Mar.　　(b) 14Mar - 20Mar.

(c) 20Mar - 26Mar.　　(d) 26Mar - 01Apr.

Figure 2: Change maps over Beira within defined residential areas according to the UA dataset at 8 different time pairs T_1, T_2. Blue pixels means that the radar reflection increased from $T_1 - T_2$ for both the VV, VH channels, red pixels means it decreased and in grey pixels, VV and VH showed opposite of each other. The changes shown are at a 5% significance level. Non-residential areas, like industry and the airport, are filtered out using the UA filter.

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Figure 2 shows that there are few significant changes in the period before the cyclone (image a) as well as after the cyclone (image d). A close inspection of image (a) shows two areas of the city with a concentration of significant changes. A thin blue line at the center of the city, comes from a water channel that exhibit changes likely due to changing water levels. The latter is a large parking area for trucks, which in Google Earth are observed as either largely full or almost empty. The rest of the city is largely void of any significant changes prior to the arrival of Idai. Following the arrival of Idai on March 14, there are a large number of changes detected between March 14 and March 20 (image b). Further, there are a substantial number of changes detected between March 20 and March 26. the changes exhibit *increased reflections* over the period of the highest cyclone impact (March 14 to 20) and *decreased reflections* in the period immediately following (March 20 to 26), potentially reflecting rebuilding efforts.

4.3 Filtering results by OSM data

To focus on socio-economic impact results are further filtered by the location of houses from OSM. Hence, impact on soil or surrounding vegetation is excluded from the results. This provide a more focused analysis. Utilizing prior knowledge on location of key infrastructure like schools, bridges,hospitals and roads, could also be used as filters and provide key operational support.

4.4 Change Detection Compared to Manually Tagged Damages

To make comparisons across damage datasets and other spatial characteristics, the analysis is done at the level of the UA grid cells and both results are filtered by the location of houses according to OSM. The severity of the cyclone impact can be assessed by counting the number of tags within each cell. *Manual tags* and *changes* have a Spearman rank correlation of 0.55, which must be considered a low correlation and shows, not surprisingly, that the *manual tags* and *changes* are two different sources of information on the cyclone's impact. For instance, a small crack in a roof, which is marked in the *manual tags* dataset, will not be captured in *changes*. Further, the *manual tags* are assessed on March 26, 11 days after the peak of the cyclone, while *changes* are assessed on March 20, 5 days after the peak of the cyclone.

5 Conclusions

This paper shows that freely available SAR data can provide timely assessment of cyclone damage, earlier than information from optical images or UAVs would be available. This can provide critical first information critical for emergency response. As ground truth for situations are never available the final validation of this methodology for assisting emergency response with damage assessments, should be field studies of actually cyclones to confirm the worst hit areas corresponds to areas with most changes, generally speaking. This is validation could be pursued in future studies. The potential for SAR based change detection as a tool for damage assessment is large, as it solves the delayed information given by optical image analysis which is hampered by clouds in the days after cyclones. In the case of Idai, Beira, the manual damage analysis was available 21 days after the peak cyclone impact whereas the our method could have provide information on the same day, few hours after the main impact.

References

[1] Weather data retrieved from WORLD WEATHER ONLINE. `https://www.worldweatheronline.com/`, 2017.

[2] Morton J. Canty, Allan A. Nielsen, Knut Conradsen, and Henning Skriver. Statistical analysis of changes in sentinel-1 time series on the google earth engine. *Remote Sensing*, 12(1):46, Dec 2019.

[3] Knut Conradsen, Allan Aasbjerg Nielsen, Jesper Schou, and Henning Skriver. A test statistic in the complex wishart distribution and its application to change detection in polarimetric sar data. *IEEE Transactions on Geoscience and Remote Sensing*, 41(1):4–19, 2003.

[4] Knut Conradsen, Allan Aasbjerg Nielsen, and Henning Skriver. Determining the points of change in time series of polarimetric sar data. *IEEE Transactions on Geoscience and Remote Sensing*, 54(5):3007–3024, 2016.

[5] Knut Conradsen, Allan Aasbjerg Nielsen, and Henning Skriver. Omnibus change detection in block diagonal covariance matrix polsar data from sentinel-1 and radarsat-2. *in preparation*, 2019.

[6] ESA. Sentinel-1 observation scenario.

[7] Thomas Esch, Mattia Marconcini, Andreas Felbier, Achim Roth, Wieke Heldens, Martin Huber, Max Schwinger, Hannes Taubenböck, Andreas Müller, and SJIG Dech. Urban footprint processor—fully automated processing chain generating settlement masks from global data of the tandem-x mission. *IEEE Geoscience and Remote Sensing Letters*, 10(6):1617–1621, 2013.

[8] Thomas Esch, Hannes Taubenböck, Achim Roth, Wieke Heldens, Andreas Felbier, Martin Schmidt, Andreas A Mueller, Michael Thiel, and Stefan W Dech. Tandem-x mission-new perspectives for the inventory and monitoring of global settlement patterns. *Journal of Applied Remote Sensing*, 6(1):061702, 2012.

[9] Allan A Nielsen, Henning Skriver, and Knut Conradsen. The loewner order and direction of detected change in sentinel-1 and radarsat-2 data. *IEEE Geoscience and Remote Sensing Letters*, 2019.

[10] OpenStreetMap contributors. Planet dump retrieved from https://planet.osm.org . `https://www.openstreetmap.org`, 2017.

[11] Thomas Pave Sohnesen, Peter Fisker, and David Malmgren-Hansen. Iariw-world bank.

[12] Shuai Xie, Jianbo Duan, Shibin Liu, Qin Dai, Wei Liu, Yong Ma, Rui Guo, and Caihong Ma. Crowdsourcing rapid assessment of collapsed buildings early after the earthquake based on aerial remote sensing image: A case study of yushu earthquake. *Remote Sensing*, 8(9):759, 2016.